WHEAT

Long-Term Effects of Tillage, Nitrogen, and Rainfall on Winter Wheat Yields in the Pacific Northwest

K. M. Camara,* W. A. Payne, and P. E. Rasmussen

ABSTRACT

Sustainable cropping systems are essential for agronomic, economic, and environmental reasons. Data from a winter wheat (*Triticum aestivum* L.)/summer fallow rotation experiment, in eastern Oregon, was used to evaluate long-term effects of tillage, N, soil depth, and precipitation on yield. The soil is a Walla Walla silt loam (coarse-silty, mixed, mesic Typic Haploxeroll). The experiment consisted of three tillage treatments (moldboard plow, offset disk, and subsurface sweep) and six N treatments. Four main time periods (1944–1951, 1952–1961, 1962–1987, 1988–1997), were identified, within which experimental treatments were consistently maintained. Depth to bedrock ranged from 1.2 to 3.0 m. Yield was significantly greater (>300 kg ha^{-1}) for the moldboard plow than for the subsurface sweep in all time periods. Yield was generally greater (>100 kg ha^{-1}) for the moldboard plow than for the offset disk, but only significantly in Time Periods 3 and 4. For Periods 1 and 2, the addition of N fertilizer tended to produce higher yields, regardless of quantity or distribution of rainfall. For Period 3, yield did not increase with the addition of more than 45 kg N ha^{-1}, which we attribute to below-normal precipitation. For Period 4, when precipitation was above average, yield increased with the addition of up to 90 kg N ha^{-1}. Results demonstrated that despite beneficial effects on soil properties, conservation tillage has tended to be less productive for this cropping system than moldboard plowing, probably due to lack of downy brome weed control in the conservation tillage systems.

The inland Pacific Northwest (PNW) has some of the highest soil erosion rates in the USA (Young et al., 1994b). Residue maintained by conservation tillage systems reduces erosion but, historically, most farmers have been wary of adopting such systems due to such perceived drawbacks as poor weed control (Bolton, 1983), inadequate planting equipment (Logan et al., 1987), and lower crop yield (Cosper, 1983). The development of new farming equipment and chemicals since the 1980s have increased the probability of obtaining crop yields similar to those of conventional, clean-tillage systems (Logan et al., 1987), and of lowering input costs. However, there are conflicting results on yield response of winter wheat to reduced tillage systems in the PNW. For example, Chastain and Ward (1992) found that growth, development, and yield of wheat were not affected by crop residue maintained at the soil surface with conservation systems, although test weight was reduced. Increased yields with conservation tillage have been attributed to the conservation of soil water (Rao and Dao, 1996; Papendick and Miller, 1977) due to decreased evaporation and cooler soil temperatures (Gauer et al., 1982) and increased infiltration (Good and Smika, 1978; Unger and McCalla, 1980; Allmaras et al., 1985; Schillinger, 1992; Tucker et al., 1971). Papendick and Miller (1977) reported that wheat yield had the potential to increase up to 20% with conservation of an additional 2 cm of water in a 25-cm precipitation zone.

In contrast, Hammel (1995) found that winter wheat yields under conservation tillage systems were reduced by an average of 565 kg ha^{-1} compared with conventional tillage methods. In a long-term tillage trial in eastern Oregon, Schillinger and Bolton (1992) found that greater quantities of surface residue in the stubble-mulch treatment contributed to reduced wheat germination and stand establishment because of poor seed–soil contact and less uniform seedbed conditions compared with plow tillage. As insufficient seed zone moisture is a major limitation in the establishment of fall-sown wheat in the semiarid PNW, small decreases in seed zone moisture can decrease yield (Schillinger and Bolton, 1992). Other reasons cited for lower yields under reduced tillage systems include cooler, wetter soil conditions (Gauer et al., 1982; Papendick and Miller, 1977), unfavorable interaction between soil physical properties and conservation systems (Cosper, 1983), phytotoxicity from previous crop residues (Kimber, 1973; Cochran et al., 1977), soil pathogens (Cook, 1980; Elliott and Lynch, 1984), and increased grassy weeds (Papendick and Miller, 1977).

One difficulty in interpreting apparently conflicting results on the effect of conservation tillage systems on crop yield is that many studies have drawn conclusions based on only a few years' data. Longer-term studies that include a wider range of weather conditions can provide data to draw more general conclusions on the advantages and disadvantages of tillage systems. Long-term studies provide perhaps the only way to determine whether agricultural practices will sustain or degrade the productive capability of the soil and allow insight into larger trends in crop production.

Historically, few if any technologies have increased winter wheat yield more than N fertilization. However, recommending optimum N rates is not an exact science, especially under dryland conditions (Rasmussen, 1981, 1996). Recent concerns over environmental quality, energy conservation, and economics have increased the need to maximize crop utilization of applied fertilizer N and to reduce excess application that may contribute

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Abbreviations: N, nitrogen; PNW, Pacific Northwest.

Table 1. Treatment history of N fertilization, tillage depth, and timing of N application for the tillage/fertility experiment at Pendleton, OR, 1945–1997.

Fertility subplot	Time period 1	2	3	4	Application timing†	Tillage depth†
	1944–1951	1952–1961	1962–1987	1988–1997		
	N treatment					
	kg ha^{-1}					cm
1	0	0	45 AN‡	0	–	20
2	11 AS‡	34 AS	45 AN	45 UAN‡	Plowing	20
3	0	0	90 AN	90 UAN	–	13
4	11 AS	34 AS	90 AN	90 UAN	Plowing	13
5	11 AS	34 AS	135 AN	135 UAN	Seeding	20
6	11 AS	34 AS	180 AN	180 UAN	Seeding	13

† Application timing and tillage depth were treatments only during Period 1 (1944–1951) and Period 2 (1952–1961).
‡ AS = ammonium sulfate; AN = ammonium nitrate; UAN = urea ammonium nitrate.

to stream or ground water contamination (Olson and Swallow, 1984). Determination of optimum N rates is best done with yield records over a period of time that includes a range of weather conditions (Rasmussen, 1996).

Soon after its inception in 1928, Oregon State University's Columbia Basin Agricultural Experiment Station, located near Pendleton, OR, initiated a number of long-term cropping system studies. One of the oldest experiments originated in 1940 to determine the effects of tillage, crop residue management, and N application on the sustainability and profitability of winter wheat–summer fallow cropping systems. The study continues to this day. Although the effects of tillage and N treatments on soil properties have been reported (Black and Siddoway, 1977; Christensen et al., 1994; Lamb et al., 1985; Rasmussen and Rohde, 1988), yield and its relation to experimental treatments and other environmental variables, e.g., rainfall and soil depth, have not.

The objective of this study was to use yield data from this experiment to evaluate the long-term effects of tillage, N, soil depth, and precipitation on yield in a winter wheat–summer fallow rotation.

MATERIALS AND METHODS

Field Design

This experiment was conducted at the Columbia Basin Agricultural Research Center (45°35′45″ N, 118°31′02″ W) near Pendleton, OR. The climate is characterized by cool, moist winters and hot, dry summers. The mean annual precipitation is approximately 420 mm, of which 70% is generally received between 1 September and 11 April. The soil is classified as Walla Walla silt loam (coarse-silty, mixed, mesic Typic Haploxeroll).

The experiment consisted of a winter wheat–summer fallow rotation with one set of plots; thus, yield was obtained only in odd years. Plots were arranged in a split-plot design with three replications. The main plot treatments were three primary tillage systems (moldboard plow, subsurface sweep, and offset disk) and six fertility subplots. The moldboard plow had a tillage depth of approximately 23 cm and approximately 7% residue cover at seeding (Rasmussen, unpublished data, 1994). The subsurface sweep had a tillage depth of approximately 15 cm and approximately 43% residue cover at seeding. The offset disk tilled at a depth of approximately 15 cm and had approximately 34% residue cover at seeding. Individual plot size was 5.5 by 140 m.

Replication 1 had an average depth to bedrock of 210 cm and was located on a slope of 3%; Replication 2 had an average depth to bedrock of 130 cm on a slope of 0 to 2%; and Replication 3 had an average depth to bedrock of 110 cm on a slope of 2%.

Primary tillage operations (plow, disk, and sweep) were performed in late March on stubble left undisturbed since the previous harvest. All plots were subsequently smoothed to a depth of 10 to 15 cm deep with a field cultivator and harrow and rod-weeded four to five times between April and October to control weeds and to reduce soil moisture loss. Nitrogen fertilizer was normally applied around 1 October, and winter wheat seeded around 10 October with a semideep furrow drill. Medium-tall soft white winter wheat was grown from 1940 to 1962, and semidwarf soft white winter wheat varieties since.

Grain yield was determined for 27 of 29 crops grown in alternate years during the 1941 to 1997 period. Due to a lack of scientific personnel at the station during the Great Depression and World War II, data collected for 1941 and 1943 were considered unreliable and were excluded from this study. Grain yield was determined by harvesting a 2.1 by 40 m swath with a self-propelled combine.

The experimental design has remained relatively unaltered since inception, but the fertility treatments, timing, and tillage depth have been modified four times to maintain relevance

Table 2. Average annual, winter (1 October–31 March), growing season (1 April–30 June), and 9-mo cropping season (1 October–30 June) precipitation for winter wheat for the four major time periods at Pendleton, OR.

Precipitation	Time period 1	2	3	4	Long-term avg.†
	1944–1951	1952–1961	1962–1987	1988–1997	
	mm				
Annual	426	424	422	429	418
Winter	297	288	299	279	270
Growing season	117	117	93	126	108
9-mo cropping season	414	405	392	405	379

† 68-yr average.

to contemporary agriculture. Therefore, the data was divided into four time periods, described below, in which treatments remained consistent. History of N fertilization, tillage depth, and timing of N application are summarized in Table 1. Precipitation averages for the time periods are given in Table 2.

Period 1 (1944–1951)

Four of the six subplots received N in the form of ammonium sulfate at a rate of 11 kg N ha^{-1}. Although this is a very low rate by modern standards, at the time many felt that the use of N in dryland wheat systems would depress yield (McGregor, 1982). The N was applied to two of these plots at seeding and to the other two plots at plowing. The last two subplots received no N fertilizer. Two of the fertilized plots (one treated at seeding and the other at plowing), and one of the unfertilized plots, were tilled to a depth of 13 cm. The other three plots were tilled to a depth of 20 cm. The experiment was seeded to the winter wheat variety Rex M-1 in 1945, spring wheat in 1947, and the winter wheat variety Elgin in 1949 and 1951.

Period 2 (1953–1961)

In 1953, the rate of ammonium sulfate was increased from 11 to 34 kg N ha^{-1}. The tillage methods and depths, and the timing of fertilizer application remained unaltered. The plots were seeded to the winter wheat varieties Elgin in 1953, Elmar in 1955, and Omar from 1957 to 1961.

Period 3 (1962–1987)

Important changes were made to the experimental design in 1962, reflecting the introduction of high yielding, N-responsive semidwarf varieties of the green revolution into regional farming systems. The initial tillage treatments, including the moldboard plow, subsurface sweep, and offset disk continued. However, tillage depth was discontinued as a treatment, and all plots were tilled to a depth of 15 cm. The fertility treatments were also revised. The four plots that previously received 34 kg N ha^{-1} as ammonium sulfate (two plots at plowing and two plots at seeding) were fertilized only at seeding. Newly introduced fertilizer treatments were 45, 90, 135, and 180 kg N ha^{-1} as ammonium nitrate. The two plots, which had previously received no N fertilizer, began receiving 45 and 90 kg N ha^{-1}. The plots were seeded to the winter wheat varieties Gaines from 1963 to 1967, Nugaines from 1969 to 1973, McDermid in 1975, Hyslop in 1977, and Stephens from 1979 to 1997.

Period 4 (1988–1997)

In 1988, the subplot that had received 0 kg N ha^{-1} from 1945 to 1961 and 45 kg N ha^{-1} from 1962 to 1987 was designated as the control, receiving 0 kg N ha^{-1}. Nitrogen rates on all other plots remained unmodified. The form and placement of N changed from broadcast ammonium nitrate to urea ammonium nitrate (32–0–0) and shanked 15 cm deep with 25 cm band spacing.

Statistical Analysis

Analysis of variance was used to test the statistical significance of the main split plot treatments and any interactive effects on wheat yield. Analyses were made for individual years and for all years within a particular time period. In subsequent analyses, total annual precipitation and growing season (1 April–30 June) precipitation plus winter (1 October–31 March) precipitation were used as covariates. Finally, soil depth × annual precipitation was used as a covariate within the four time periods to test for interactive effects of these two variables on yield. Statistical models were evaluated using SYSTAT's GLM module (SYSTAT, 1996).

RESULTS

Tillage

The significance of tillage, N fertilizer, and their interaction on winter wheat yield is summarized in Table 3. There was no interactive effect between tillage and N for any year except 1997. When 1997 data were combined with those from other years in Period 4, there was no interactive effect.

Tillage had a significant effect in each time period (Fig. 1). In all four periods, the moldboard plow treatment had approximately 300 to 400 kg ha^{-1} greater yield than the subsurface sweep treatment. Winter wheat yield depression under conservation tillage systems when compared with conventional tillage practices has also been reported by Cochran et al. (1977), Papendick and Miller (1977), and Payne et al. (2000). In the present study, yield reduction was probably due largely to poor control of the invasive grass species downy brome (*Bromus tectorum* L.). Field notes dating back to 1961 repeatedly report severe downy brome infestations in subsurface sweep plots. These qualitative observations nearly always described downy brome infestation as less severe in the offset disk treatment than in the subsurface sweep treatment, and as negligible in the moldboard plow treatment. The importance of weed control to the suc-

Table 3. Statistical significance of tillage and fertilizer treatments and their interaction, on winter wheat yield for the tillage/fertility experiment at Pendleton, OR, 1945–1997.

Time period	Year	Tillage treatment	Fertilizer treatment	Tillage × Fertilizer
1	1945	NS†	NS	NS
1	1947	NS	NS	NS
1	1949	***	NS	NS
1	1951	*	***	NS
2	1953	NS	***	NS
2	1955	*	***	NS
2	1957	NS	***	NS
2	1959	**	NS	NS
2	1961	NS	***	NS
3	1963	NS	***	NS
3	1965	*	***	NS
3	1967	NS	***	NS
3	1969	NS	***	NS
3	1971	NS	***	NS
3	1973	NS	NS	NS
3	1975	NS	NS	NS
3	1977	NS	*	NS
3	1979	NS	NS	NS
3	1981	NS	***	NS
3	1983	NS	***	NS
3	1985	***	NS	NS
3	1987	NS	**	NS
4	1989	NS	***	NS
4	1991	NS	*	NS
4	1993	***	***	NS
4	1995	***	***	NS
4	1997	***	***	*

* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.
† NS = not significant.

cess of conservation tillage systems in the PNW has been well documented (Young et al., 1994 a,b). Similarly, Bond et al. (1971) found that a stubble–mulch tillage system increased weed populations by two to three times compared with moldboard plowing, and Fenster et al. (1969) found that downy brome control with stubble–mulch tillage systems was not as consistent as with a one-way disk or moldboard plow.

It is also possible that lower yields were in part due to decreased N mineralization associated with conservation tillage (McCalla and Army, 1961; Winterlin et al., 1958; Harris, 1963). Lamb et al. (1985) found that soils of a stubble–mulch tillage system accumulated only about 70% as much NO_3–N as plowed soils at two sites, and Harris (1963) found soil NO_3–N accumulations to be depressed under stubble–mulch tillage at seeding time in the Great Plains. Payne et al. (2000) reported that wheat grain N content was significantly reduced in conservation tillage treatments in a wheat–dry pea rotation experiment, suggesting possibly reduced N mineralization. Reduced mineralization may be caused by increased N immobilization associated with higher residue systems (Cochran et al., 1980; Doran, 1980). However, the lack of a tillage $\times$ N interaction in this study suggests that greater N immobilization was not a factor in grain yield reduction with conservation tillage. Furthermore, this was unlikely, as the 135 and 180 kg N ha^{-1} rates should have provided sufficient N to eliminate any N deficiency and alleviate yield differences between tillage treatments.

Yields with the moldboard plow system were significantly higher than with the offset disk tillage treatment in Periods 3 (1962–1987) and 4 (1988–1997). The same trend was evident for mean yield in Periods 1 (1944–1951) and 2 (1952–1963), but differences were not statistically significant (Fig. 1). Mean yields tended to be higher, although only significantly in Period 2, for plots tilled with the offset disk than for plots tilled with the subsurface sweep, except in Period 4. In this last period, this trend reversed, and mean yield with the subsurface sweep was approximately 200 kg ha^{-1} greater than with the offset disk. This may be due to improved chemical herbicides, which provide greater control of downy brome than was possible during Period 3.

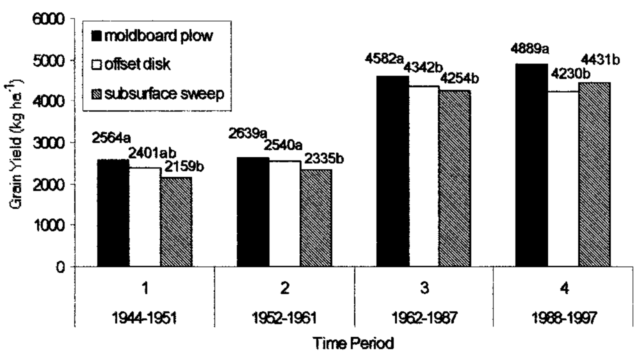

Fig. 1. The influence of tillage on winter wheat for the four major time periods of the tillage/fertility experiment at Pendleton, OR, 1945–1997. Values without a letter in common are significantly different at the 0.05 probability level, according to Tukey's HSD.

Nitrogen

Fertilizer application affected wheat grain yield for 19 of the 27 yr of the study (Table 3). When annual grain yield data were pooled within the four time periods, fertilizer was a statistically significant variable for all periods but the first (1944–1951), when the maximum N rate was only 11 kg N ha^{-1}. Even at this low N rate, however, there was a tendency for yield to increase compared with the unfertilized treatment (Fig. 2a). For

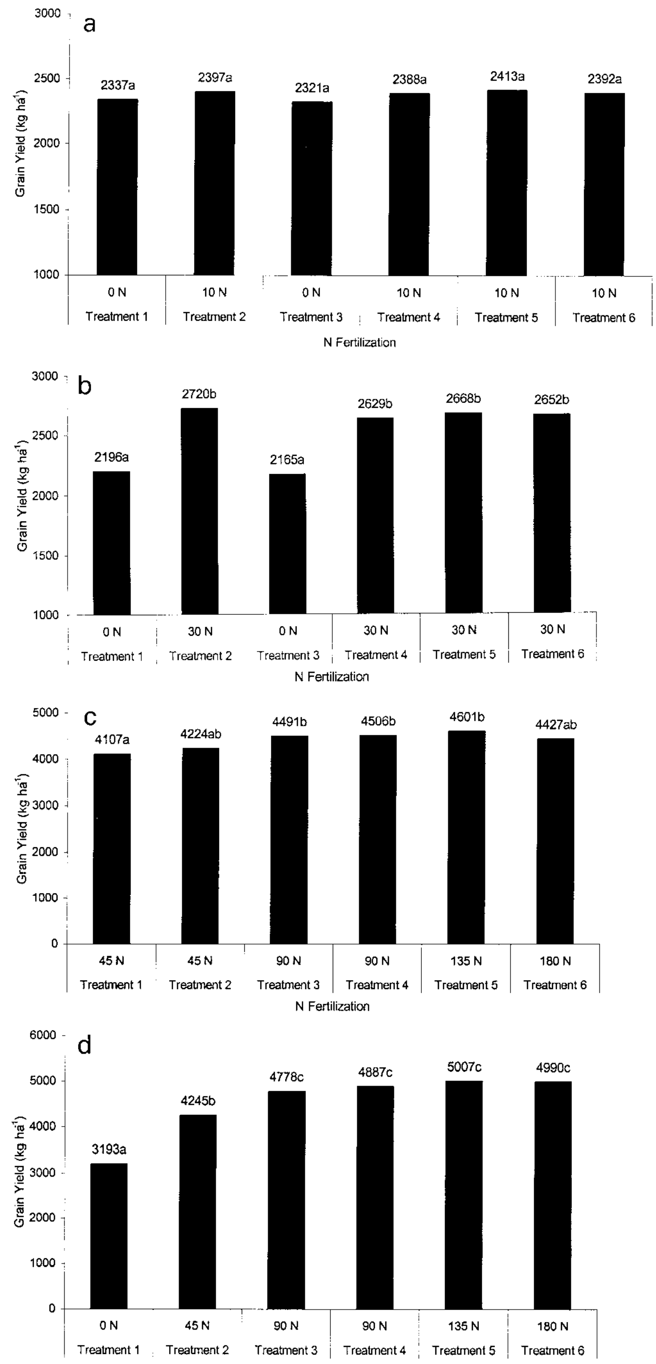

Fig. 2. The influence of N fertilization during (a) Period 1 (1944–1951); (b) Period 2 (1952–1961); (c) Period 3 (1962–1987); and (d) Period 4 (1988–1997) on winter wheat for the tillage/fertility experiment at Pendleton, OR, 1945–1997.

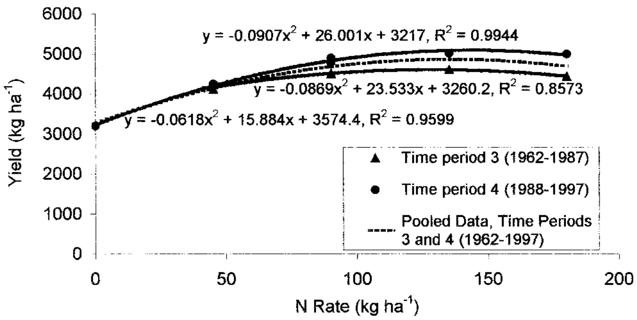

Fig. 3. Long-term response of soft white winter wheat to N fertilization for Period 3 (1962–1987), Period 4 (1988–1997), and pooled data for Periods 3 and 4 (1962–1997) for the tillage/fertility experiment at Pendleton, OR, 1945–1997.

Period 2 (1952–1961), grain yield increased significantly with the addition of 34 kg N ha^{-1} (Fig. 2b).

For Period 3 (1962–1987), grain yield did not significantly increase with the addition of more than 45 kg N ha. Insignificant yield differences between fertility Subplot 1 and 2 (which received 45 kg N ha^{-1}) and Subplots 3 and 4 (which received 90 kg N ha^{-1}) could be attributed to the use of ammonium sulfate fertilizer during Periods 1 and 2. A residual sulfur or N response may be responsible for slightly higher yields for Plots 2 and 4 (Table 1, Fig. 2c). Maximum mean yield was obtained at an application rate of 135 kg N ha^{-1} (Fig. 2c).

For Period 4 (1988–1997), average grain yield increased with the addition of 45 and 90 kg N ha^{-1} (Fig. 2d). There was no significant yield increases at greater rates of N. While yields were not significantly different between 90 and 135 kg N ha^{-1}, maximum mean yield was obtained at an application rate of 135 kg N ha^{-1}.

Data in Fig. 3 can be used to accommodate Rasmussen's (1996) recommendation that N rates are best done with yield records over a period of time that includes a range of weather conditions. Despite the wide-range of time that is encompassed in Periods 3 and 4 (1962–1997), N response is relatively conservative. Equations fitted to the data in Fig. 3 could be of potential use for long-term economic analyses, at least for Pendleton conditions.

Precipitation

Total precipitation was a significant ($p < 0.01$) covariate for all time periods except Period 4 (1988–1997) (Table 4). Growing season (1 April–30 June) and winter precipitation (1 October–31 March) were significant ($p < 0.01$) covariates for all time periods except Period 1 (1944–1951) (Table 4). Grain yield was positively correlated with annual precipitation (Fig. 4a) and with the 9-mo growing season precipitation (1 October–30 June) (Fig. 4b), as expected under dryland conditions. Similar correlations were seen for growing season and winter precipitation.

Interaction between Soil Depth and Precipitation

There was a significant ($p < 0.01$) interaction between the covariates soil depth and annual precipitation in all but the fourth time period (Table 5) when growing season (1 April–30 June) precipitation was the highest (Table 2). The nature of this interaction is illustrated in Fig. 5. In very dry years (<300 mm), yield was approximately 1000 kg ha^{-1} greater in relatively deep soils (>2.8 m) compared with shallow soils (<1.3 m). However, as precipitation increased to approximately 400 mm or more, the effect of soil depth diminished. Similarly, Rasmussen (1991) concluded that wheat yield was not affected by soil depth when growing season precipitation was above average, but was 10 to 20% less in shallow soils when growing season precipitation was below average. Shallow soils store less water and thus have a lower yield capability than deep soils in dry years (Rasmussen et al., 1989). Rasmussen (1981) found that a 210 cm deep soil produced a maximum yield of 5034 kg ha^{-1}, while a nearby 110 cm deep soil reached a maximum yield of only 4026 kg ha^{-1}.

When precipitation was >500 mm, yield decreased by approximately 1500 kg ha^{-1}, regardless of soil depth (Fig. 5). The decrease in yield was potentially due to disease, lodging, or N fertilizer leaching.

Yield Evolution

Figure 6 shows the 5-yr moving average of winter wheat yield from 1945 to 1997. Wheat yield has improved since the 1940s with the introduction of new

Table 4. Effects of fertilizer and tillage on winter wheat yield for the four time periods at Pendleton, OR, using annual precipitation or winter (1 October–31 March) and growing season (1 April–30 June) precipitation as covariates.

		Time period			
		1	2	3	4
Source of variation	df	1944–1951	1952–1961	1962–1987	1988–1997
			Analysis of variance		
Annual precipitation	1	**	***	***	NS†
Tillage	2	**	***	***	***
Fertilizer	5	NS	***	***	***
Tillage × Fertilizer	10	NS	NS	NS	NS
			Analysis of variance		
Growing season precipitation	1	NS	***	***	***
Winter precipitation	1	NS	***	***	**
Tillage	2	**	***	***	***
Fertilizer	5	NS	***	***	***
Tillage × Fertilizer	10	NS	NS	NS	NS

** Significant at the 0.01 level.
*** Significant at the 0.001 level.
† NS = not significant.

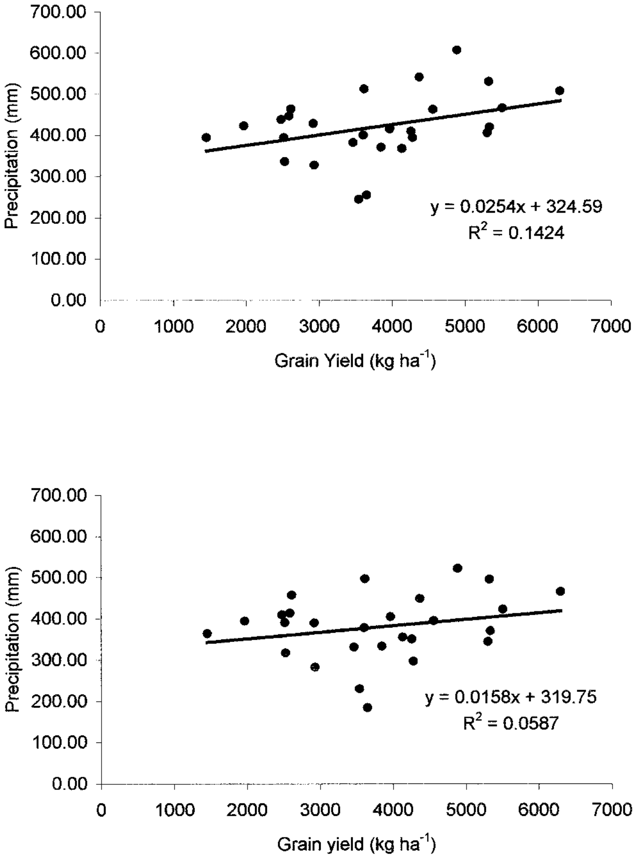

Fig. 4. The influence of (a) annual precipitation, and (b) 9-month cropping season (1 October–30 June) precipitation on winter wheat for the tillage/fertility experiment at Pendleton, OR, 1945–1997.

technology (Fig. 6). Yield increase was minimal at first, and became more rapid soon after 1960 due primarily to the introduction of semidwarf varieties that were responsive to increasing rates of fertilizer application. The new semidwarf varieties also matured earlier, and therefore were less susceptible to drought.

Because higher yields require larger quantities of nutrients from the soil, the low moving averages in Fig. 6 also illustrates the limited yield increase that improved varieties would attain without N addition, and supports the conclusion of Ridley and Hedlin (1980) that increased use of N fertilizer has had the most dramatic influence on increasing crop yields since the 1950s, in combination with disease resistant varieties to a lesser effect.

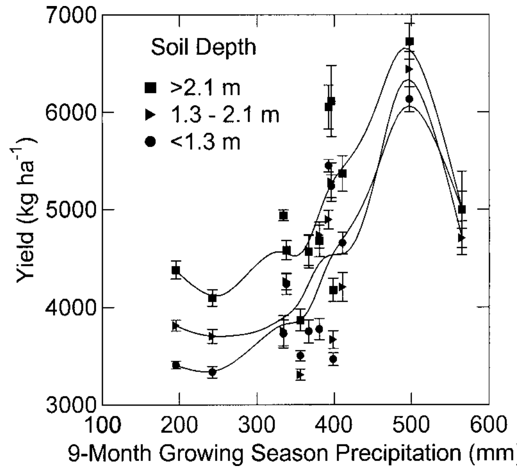

Fig. 5. The influence of soil depth and 9-mo cropping season (1 October–30 June) precipitation on winter wheat yield, during Period 3 (1962–1987), for the tillage/fertility experiment at Pendleton, OR, 1945–1997. Points represent the mean yield of individual plots. The bars indicate ±1 SE. Curves were generated using distance-weighted least squares.

Finally, even without the low 1997 yield caused by poor rainfall, data since 1980 in Fig. 6 serve to illustrate that the rate of yield increase, and therefore our ability to keep pace with rising global demand for wheat (Brown, 1995; Reynolds et al., 1996) has fallen considerably since the period 1960–1980.

DISCUSSION

The consistently depressed yields associated with conservation tillage illustrate why, we believe, there has been minimal adoption of this practice in eastern Oregon and other parts of the Columbia Basin, despite well-documented beneficial effects of such systems on soil properties. For example, Rasmussen et al. (1989) found that after 50 yr of stubble–mulch tillage, soils in eastern Oregon had 33% more soil organic matter (SOM) in the top 7.5 cm than those that were conventionally plowed. Similarly, Rasmussen and Rohde (1988) found that organic N and C in the top 75 mm of soil were 26 and 32% higher, respectively, in two stubble–mulch systems than in conventional plow tillage.

We believe the main reason for yield decrease under conservation tillage, in our experiment, was inadequate weed control. Similarly, after examining 80 yr of data at Lethbridge, AB, Freyman et al. (1982) suggested the main factor contributing to increased wheat yield since

Table 5. Effects of fertilizer and tillage on winter wheat yield for the four time periods at Pendleton, OR, using annual precipitation and soil depth as covariates.

		Time period			
		1	2	3	4
Source of variation	df	1944–1951	1952–1961	1962–1987	1988–1997
Soil depth × Annual precipitation	1	**	***	***	NS†
Tillage	2	***	***	***	***
Fertilizer	5	NS	***	***	***
Tillage × Fertilizer	10	NS	NS	NS	NS

** Significant at the 0.01 level.
*** Significant at the 0.001 level.
† NS = not significant.

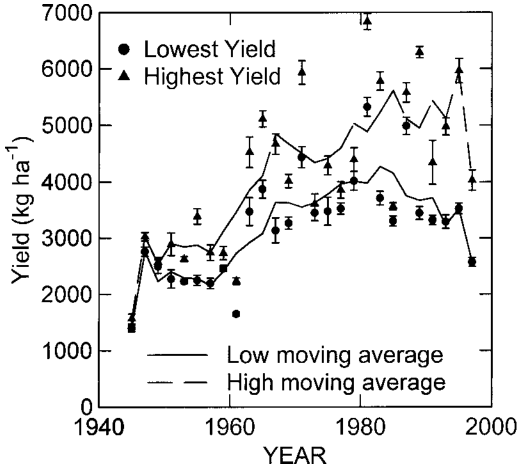

Fig. 6. Five-year moving average of winter wheat yields for the tillage/fertility experiment at Pendleton, OR, 1945–1997.

1963 was chemical weed control. It follows that further reduction in herbicide costs and increased efficiency of weed control would go a long way toward making reduced tillage systems more practical in the PNW (Young et al., 1994b).

Despite the yield disadvantage of the conservation tillage system suggested by this study and by farmer reluctance to adopt conservation or zero tillage systems in the inland Northwest, current rates of soil degradation will eventually render the presently used system unsustainable in terms of long-term soil productivity. Previous research on this experimental plot by Rasmussen and Rohde (1988) showed 26 and 32% higher organic N and C, respectively, in the top 75 mm of soil in the two stubble–mulch systems than with the moldboard plow. This was recognized long ago by scientists in the region (Stephens, 1939; Smith et al., 1946).

Most farmers presently continue to sacrifice long-term sustainability for the sake of shorter-term profitability because of the low-to-negative profitability of dryland wheat-based systems. Reductions in herbicide costs, increased efficiency of weed control, and further understanding of the influence of surface residue on seed germination, N mineralization and immobilization, and weed populations will perhaps eventually result in greater yields and greater adoption of conservation tillage systems in the PNW.

The degree to which results from our long-term study can be extrapolated to other sites is unclear because of the uniqueness of this experiment. Of all the long-term experiments in North America reviewed by Mitchell et al. (1991), the tillage/fertility experiment (the focus of this study) was the only one in which the study of tillage effects on productivity was an objective. Tillage is mentioned as an historical treatment in the Sanborn Field at the University of Missouri-Columbia by Mitchell et al. (1991), but none of the cropping systems utilized fallow, and all plots were fall-plowed (Gantzer et al., 1991). Winter wheat–summer fallow cropping systems have been practiced in the U.S. Great Plains, but weather patterns, including rainfall distribution and temperature extremes, are very different.

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